Modeling of Coastal Ocean Flow Fields

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LONG-TERM GOALS

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

SCIENTIFIC OBJECTIVES

To apply numerical circulation models to process studies and to simulations of continental shelf and slope flow fields, including the nearshore surf zone, to help achieve understanding of the flow dynamics.

APPROACH

Numerical finite-difference models based on the primitive equations, balance-type intermediate equations, and the shallow-water equations are applied to two- and three-dimensional flow problems relevant to the dynamics of continental shelf and slope flow fields. At present, the Blumberg-Mellor sigma coordinate POM model is being utilized for studies with the primitive equations. A shallow-water equation model has been developed and applied to studies involving vorticity dynamics of currents in the nearshore surf zone. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

Model studies of two-dimensional (variations across-shore and with depth, uniformity alongshore), time-dependent, wind-forced, stratified downwelling circulation on the continental shelf (Allen and Newberger, 1996) have shown that the near-bottom offshore flow can develop time- and space-dependent fluctuations involving spatially-periodic separation and reattachment of the bottom boundary layer. This results in the formation of slantwise circulation cells with horizontal scales 2-4 km and vertical scales 20-60 m. Based on the observation that the potential vorticity, initially less than zero everywhere, is positive in the region of the fluctuations, this behavior was identified as finite amplitude slantwise convection resulting from a symmetric instability. To support that identification, we have pursued a study with the objective of analytically determining the linear stability of a near-bottom oceanic flow over sloping topography with conditions dynamically similar to those in the downwelling circulation. A second objective is to establish a link between the instabilities observed in the wind-forced downwelling problem and the results of recent theoretical studies of bottom boundary layer behavior in stratified oceanic flows over sloping topography (e.g., Garrett, MacCready, and Rhines, 1993). These objectives have been addressed by investigating the two-dimensional linear stability and

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the nonlinear behavior of the steady, inviscid, “arrested Ekman layer” solution produced by transient downwelling in one-dimensional models of stratified flow adjustment over a sloping bottom. Further linear stability analyses and numerical experiments addressing both two and three-dimensional aspects of symmetric instabilities in bottom boundary layers have also been undertaken.

Numerical experiments addressing the nature of nonlinear, finite amplitude shear instabilities of alongshore currents in the surf zone through the solution to idealized, forced, dissipative, initial-value problems have been performed. Bottom topographies with constant slope (i.e., a plane beach), with an alongshore-uniform sand bar, and with an alongshore variable sand bar, are used with periodic boundary conditions in the alongshore direction. Forcing effects from obliquely incident breaking surface waves are calculated from gradients in the radiation stress tensor. These are determined using the formulation of Thornton and Guza (1986) generalized, for the alongshore variable topography, to two-dimensional situations. Dissipative effects are modeled by linear bottom friction.

A new, approximate, extended-geostrophic model for balanced, rotating, stratified motion governed by the primitive equations has been systematically derived by using a small Rossby number expansion in Hamilton's Principle (Allen, Holm, and Newberger, 1998).

RESULTS

A linear stability analysis of the steady, inviscid, two-dimensional, “arrested Ekman layer” (Allen and Newberger, 1998) shows that this flow is unstable to symmetric instabilities and confirms that a necessary condition for instability is positive potential vorticity in the bottom layer. Numerical experiments show that for two-dimensional initial-value problems the unstable, time-dependent, nonlinear behavior in the boundary layer involves the formation of slantwise circulation cells with characteristics similar to those found in the wind-forced downwelling circulation. An extension of the linear stability analysis to allow for three-dimensional disturbances shows the existence of additional baroclinic instabilities with variations in both the across-shelf and alongshore directions. Corresponding three-dimensional numerical experiments for the “arrested Ekman layer” initial-value problem show growth of instabilities with evolution in time from quasi two-dimensional slantwise circulation cells to larger horizontal scale three-dimensional baroclinic disturbances (Allen and Newberger, 1999).

Numerical experiments (Allen, Newberger, and Barth, 1999) show that symmetric instabilities develop and form circulation cells in the bottom boundary layer in the basic two-dimensional spin-down problem of a depth-independent coastal jet in a stratified ocean over sloping continental shelf topography when the transient Ekman transport in the bottom boundary layer is down slope. Results from three-dimensional spin-down experiments indicate that finite amplitude symmetric instabilities can develop in the bottom boundary layer. Initially, these instabilities form circulation cells similar to those found in two-dimensions. Subsequently, these cells develop secondary baroclinic instabilities that result in time-dependent disturbances of larger horizontal scale (Figure 1), similar to those found in the three-dimensional “arrested Ekman layer” experiments.

In the study of nonlinear shear instabilities of alongshore currents in the surf zone over plane beaches (Allen, Newberger and Holman, 1996), the nature of the flow depends on a dimensionless parameter Q, which is the ratio of an advective to a frictional time scale. For Q above a critical value, instabilities develop. A robust characteristic of these instabilities is the rapid evolution, after initial growth at the

wavelength of the most unstable linear mode, into larger-wavelength, nonlinear, propagating, unsteady wavelike disturbances. In contrast, with shore-parallel sand bar topography and with forcing from the Thornton-Guza (1986) submodel, as Q is increased, the flow becomes increasingly unsteady exhibiting a transition from equilibrated shear waves to a turbulent shear flow (Slinn, Allen, Newberger, and Holman, 1998). The results with alongshore-uniform sand bar topography point to the possible existence in the nearshore surf zone of an energetic eddy field associated with instabilities of the alongshore current. Results from experiments with alongshore variable sand bars (Slinn, Allen, and Holman, 1998) show significant influence of alongshore topographic variability on the nearshore circulation. In particular, one notable feature is the tendency for contours of both the time mean and the root mean square vorticity fields to align along contours of constant depth.

Results of numerical experiments concerning instability of a baroclinic jet show that the new extended-geostrophic model derived by Allen, Holm, and Newberger (1998) gives accurate approximate solutions to the primitive equations with errors substantially smaller than found with either a quasi-geostrophic (QG) or a geostrophic momentum (GM) model.

IMPACT/APPLICATIONS

Studies of the dynamics of a stratified coastal ocean model over continental shelf topography under downwelling conditions show new flow features. These include the formation and structure of downwelling fronts and the development of finite amplitude symmetric and baroclinic instabilities in the bottom layer. The occurrence of symmetric and baroclinic instabilities in the bottom boundary layer appears to be a potentially important and robust feature of transient downwelling circulation on the continental shelf. The results of the study of nonlinear shear instabilities of alongshore currents in the nearshore surf zone indicate the possible existence over plane beaches of new finite-amplitude shear waves with properties not predicted by linear theory and the possible presence over barred beaches of an energetic eddy field.

TRANSITIONS

RELATED PROJECTS

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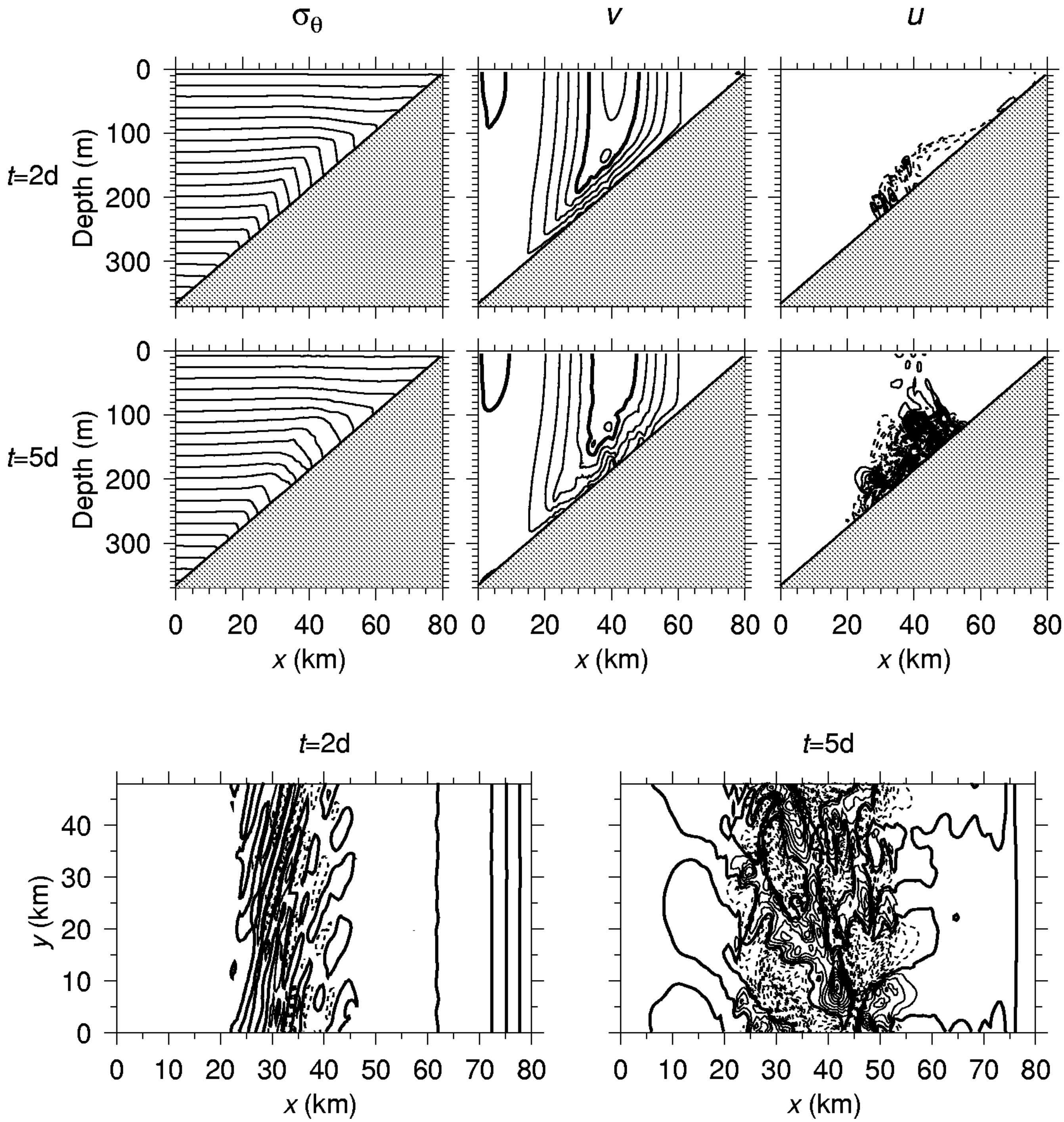

Figure 1. Results of a numerical experiment for a three-dimensional spin-down problem (Allen, Newberger, and Barth, 1999). Fields of density σ_θ, alongshore velocity v, and across-shelf velocity u at $y = 24$ km at $t = 2$ d (top) and at $t = 5$ d (middle). Contour intervals are 0.4 kg m^{-3}, 0.1 m s^{-1} and 0.05 m s^{-1}. Across-shelf velocity u along the near-bottom surface $\sigma = -0.88$ on the same two days (bottom). Contour interval is 0.02 m s^{-1}. N^2(t = 0) = 2.25 x 10^{-4} s^{-2}, max $v(t = 0)$ = 0.75 m s^{-1}, horizontal diffusion coefficient A_H = 4 m^2 s^{-1}, bottom slope $\alpha = 0.0045$, slope Burger number $S = \alpha^2 N^2/f^2 = 0.42$, Δx=0.5 km, and 45 σ levels.